SNAP
Off & On-Axis
Preliminaries Optical Configurations

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Preliminaries optical configurations for the Supernova/Acceleration Probe (SNAP) Mission are presented here. The main goal of this report is to presents the possibilities for SNAP baseline designs. The off and on-axis optical designs, consider a telescope with clear aperture of 2.0 meters in diameter producing a system focal ratio F_s/10, optimized over a 1 Deg^2 of field of view.

1- SNAP "OFF-AXIS" DESIGN

It is well know that the three-mirror telescope, as explored by Maurice Paul (1935) is capable of well correct optical aberrations produced by a parabolical primary mirror across wide field of view at fast focal ratio. Most of these three-mirror telescope designs have not been attractive for astronomy because of obscurations problems. A three-mirror telescope type was developed and built by McGraw et al in 1982, optimized across a 1Deg field, producing a 22-23% by area of obscuration with images of 0.2 Arcsec (RMS) at the border of 1x1 Deg field.

Looking more accurately the Paul geometry, we can see it as a reflective Schmidt plate corrector of an afocal Cassegrain telescope. Adopting this geometry and avoiding the huge obscuration produced by these designs we explore a three-mirror off-axis system for the SNAP telescope.

Off-axis systems using decentered mirrors was investigated in 1953 by A. Kutter, named by him as *"Schiefspiegler"* system, for "oblique mirror" in German. Meanwhile at this time off-axis systems were limited to small instruments and amateurs telescopes because of the challenges and limitations to produce an accurate and smooth large off-axis aspheric (>1m) mirror surfaces. More recently solar astronomy has successfully super-polished off-axis primary mirrors for coronagraph designs (Smartt, 1996) and the SOLAR-C, a 0.5m off-axis coronagraphic reflecting telescope which is now being built on Haleakala to the Mees Solar Observatory, (http://www.solar.ifa.hawaii.edu/solarc.html). Also several projects have proposed telescopes using larger off-axis primary mirror;

- ATST – Advanced Technology Solar Telescope, National Solar Observatory (NSO-NSF), an off-axis Gregorian configuration using a 4m off-axis primary mirror with 5X5 Arcmin of field at F_s/3.0, (http://www.sunspot.noao.edu/ATST/index.html),

- NPT – New Planetary Telescope, NASA's Infrared Telescope Facility, an off-axis configuration using a 6.5m off-axis primary producing simultaneously two modes, one wide-field mode (Paul) optimized across 2X2 Deg field of view at F_s/3.0 and a narrow-field mode (Gregorian) optimized across 2X2 Arcmin field at F_s/15, Moretto & Kuhn, (2000), Joseph et al (2000), (http://irtf.ifa.hawaii.edu/NPT_irtf/npt.html),

- HDRT - High Dynamic Range Canada-France-Hawaii Telescope, an off-axis configuration using 6X6.5m off-axis telescope, with the light gathering power of a "conventional" 15 m telescope, producing simultaneously two modes, one wide-filed mode (Paul) optimized across 1x1 Deg^2 field at Fs/1.56 and a narrow-field mode (Gregorian) optimized across 3X3 Arcmin field at F_s/15. Contact: Jeff Kuhn", kuhn@pelea.ifa.hawaii.edu.

One of baselines configurations proposed for the SNAP telescope is a three mirrors *"Off-Axis"* system producing an unobstructed 2.0m aperture in diameter with 1 Deg^2 of field at F_s/10, specifications guided by science issues (ref. S. E. Deustua). The SNAP *"Off-Axis"* design is an off-axis section of a concentric, on-axis configuration in which the primary mirror is a circular decentered piece of a concentric mirror, the parent mirror.

Figure 1 shows the SNAP baseline *"Off-Axis"* design layout, the primary M1 is an off-axis section of 2.0m F_1 /5.186 of a F_{1P}/1.421 7.30m prolate spheroid (ellipsoid) parent primary mirror PM1. The secondary M2 is an effective F_2/4.275 1.00 m diameter off-axis section of a F_{2P}/1.470 2.91m aspherical parent mirror PM2. The tertiary M3 is an effective F_3/6.248 1.24m diameter off-axis section (or a 1.1x1.1 m^2 square mirror) of an F_{3P}/2.767 2.8m aspherical parent mirror PM3. Table 1 presents the prescription of the design.

Table 1 *– The "Off-Axis" optical prescription for the SNAP F_s/10 design optimized across 1x1 Deg FOV. The effective focal length is EFL=20000mm and system plate scale is 10.3132 arcsec/mm. The column "K + Asph" shows the surface conic coefficient plus the 4^{th} (A), 6^{th} (B), 8^{th} (C) and 10^{th} (D) order deformation coefficients respectively for each surface* $\boldsymbol{M_i}$. *See Figures 4, 5 and 6 for the sag equations of each surface* $\boldsymbol{M_i}$.

Surface M_i	***Curvature Radius*** *[mm]*	***K + Asph.***	***Thickness from M_i to M_{i+1}*** *[mm]*	***Off-Axis Optical Clear Aperture***	***Parent Mirror***	***Deviation from the best-fit-sphere*** *[mm]*
M1 Primary	*-20744.807*	*-0.9601 A, B*	*-6464.1809*	*2.00m F_1/5.186*	*7.30m F_{3P}/1.421*	*-0.8283 (see Figure 4)*
M2 Secondary	*-8551.657*	*0.0000 A, B, C, D*	*-6464.1809*	*1.00m F_2/4.275*	*2.91m F_{3P}/1.470*	*-0.5593 (see Figure 5)*
M3 Tertiary	*-15497.513*	*0.0000 A, B*	*-6464.1809*	*(1.1x1.1)m F_3/6.248*	*2.80m F_{3P}/2.767*	*-0.0655 (see Figure 6)*
FP Focal Plane	*FLAT*	*0.0000*	---	*349.067mm x 349.067 mm*	----	

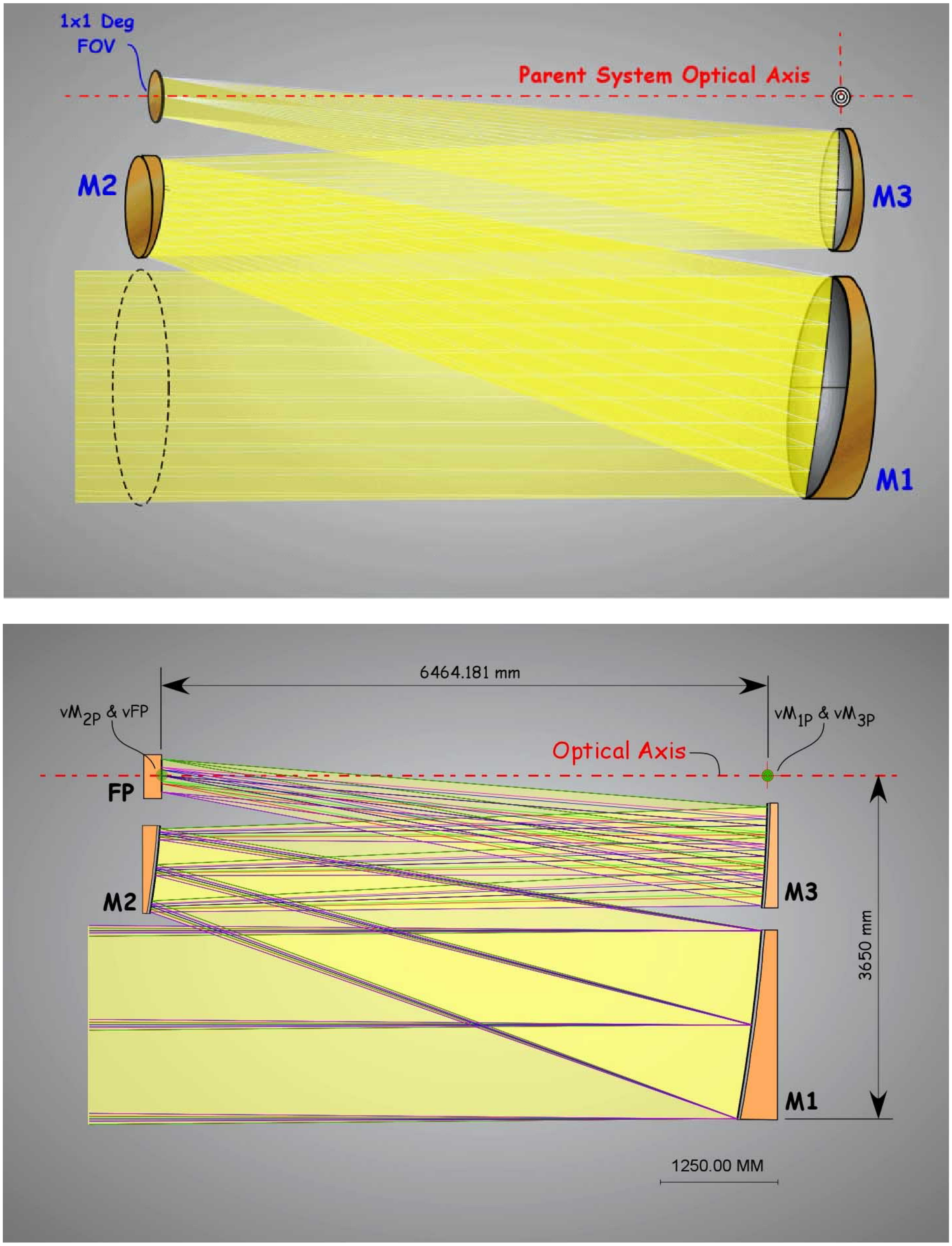

Figure 1 – "Off-Axis" configuration for SNAP. *A three-mirror decentered configuration that produces an unobstructed 2.0m aperture F_s/10 optimized across a 1x1Deg FOV. The mirrors decenters were constrained to the dimensions of a payload that could be launched in the fairing 4m in diameter room of DeltaIII rocket.*

Note that "Off-Axis" SNAP is **not a tilted but a decentered design**, with its symmetry axis centered on the optical axis of the parent primary mirror. This configuration preserves many of the optical performance, tolerances and sensitivity characteristics of the parent concentric system. Also the design has the vertexes of M1&M3 and M2&FP coincident and collinear to the optical axis of the system, that was intentionally constrained during the optical optimization having in mind facilitating the alignment/tolerances and sensitivity tasks.

The 20000mm system effective focal length (EFL) assures a plate scale of S=10.3132 Arcsec/mm that gives a focal plane of dimension 349.067 x 349.067 mm^2. The optical performance of the system optimized over the 1Deg^2 FOV is represented by the encircled energy (EED) distribution for several positions F_i (x,y) across the FOV as showed in figure 3 . The geometric spots for the several positions F_i(x,y) are presented in figure 2, note that the frame dimensions – 1x1 and 0.5x0.5 Deg – is not in the same scale than the spots diameters. The system achieves an excellent control the encircled energy. Most field positions concentrate almost **100% of encircled energy inside of a circle of 0.050 Arcsec in diameter**, yielding in a sharp point spread function (PSF) with a medium FHWM of 0.020 Arcsec.

The three-mirrors deviate from a best-fit-sphere by 0.07 to 0.85mm, as presented in figures 4,5 and 6, a mild aspheric departures that is not difficult to manufacture or test. Several techniques to manufacture off-axis mirror has been developed in the last years, using stressed mirror technique – segments of primary mirror of Keck Telescope - or two axis computer polishing techniques. Several optical manufacturing organizations, REOSC (France), Mirror Lab (University of Arizona) and Raytheon have expressed their strong interest in fabrication of large off-axis aspheric optics, up to 6.5-8.0m in diameter. Also Kodak has publicized (http://www.kodak.ch/US/en/government/ias/optics) that they can shape off-axis aspheric optics surface with a custom computer numerical control (CNC) off-axis grinding machine, in blank size from 0.25 to 2.5m!

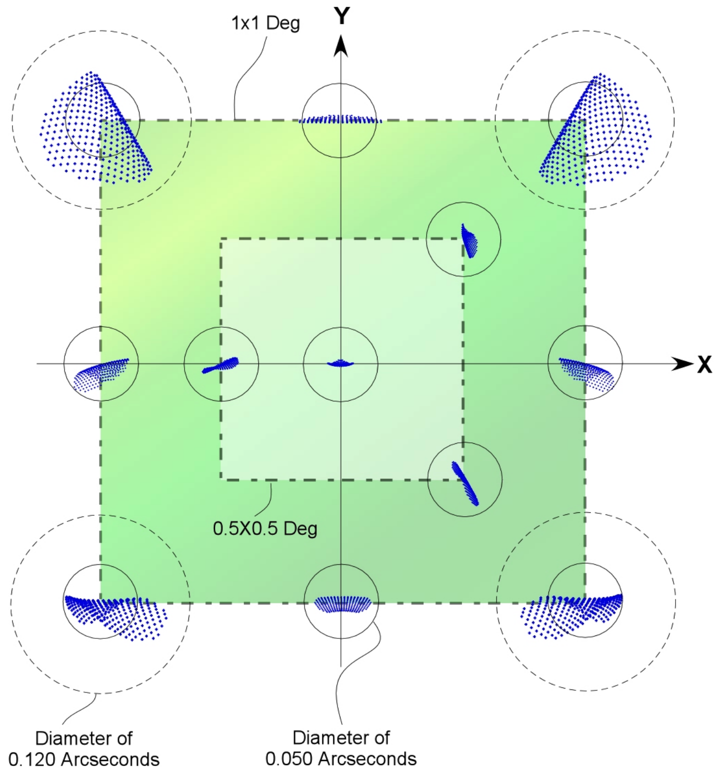

Figure 2 *– The “Off-Axis” SNAP design geometrical spots performance. Spot are computed over a 1X1 Deg FOV. Note that the frame dimension is not in the same scale than the spots diameters.*

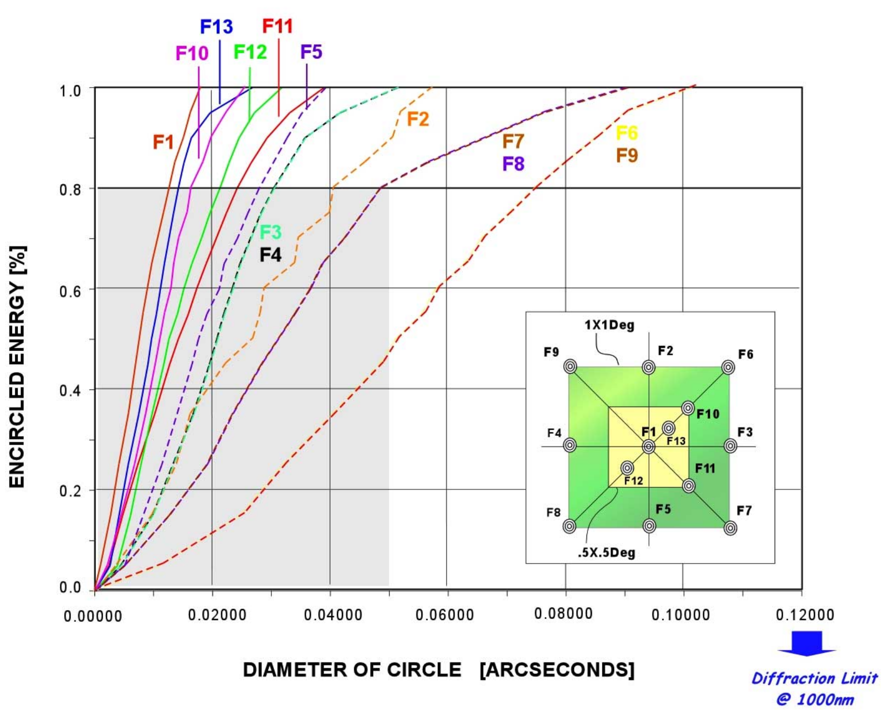

Figure 3 *– The “Off-Axis” SNAP design encircled energy diameter for each field position $F_i(x,y)$ across the 1X1 Deg FOV as represented at right-side of the figure.*

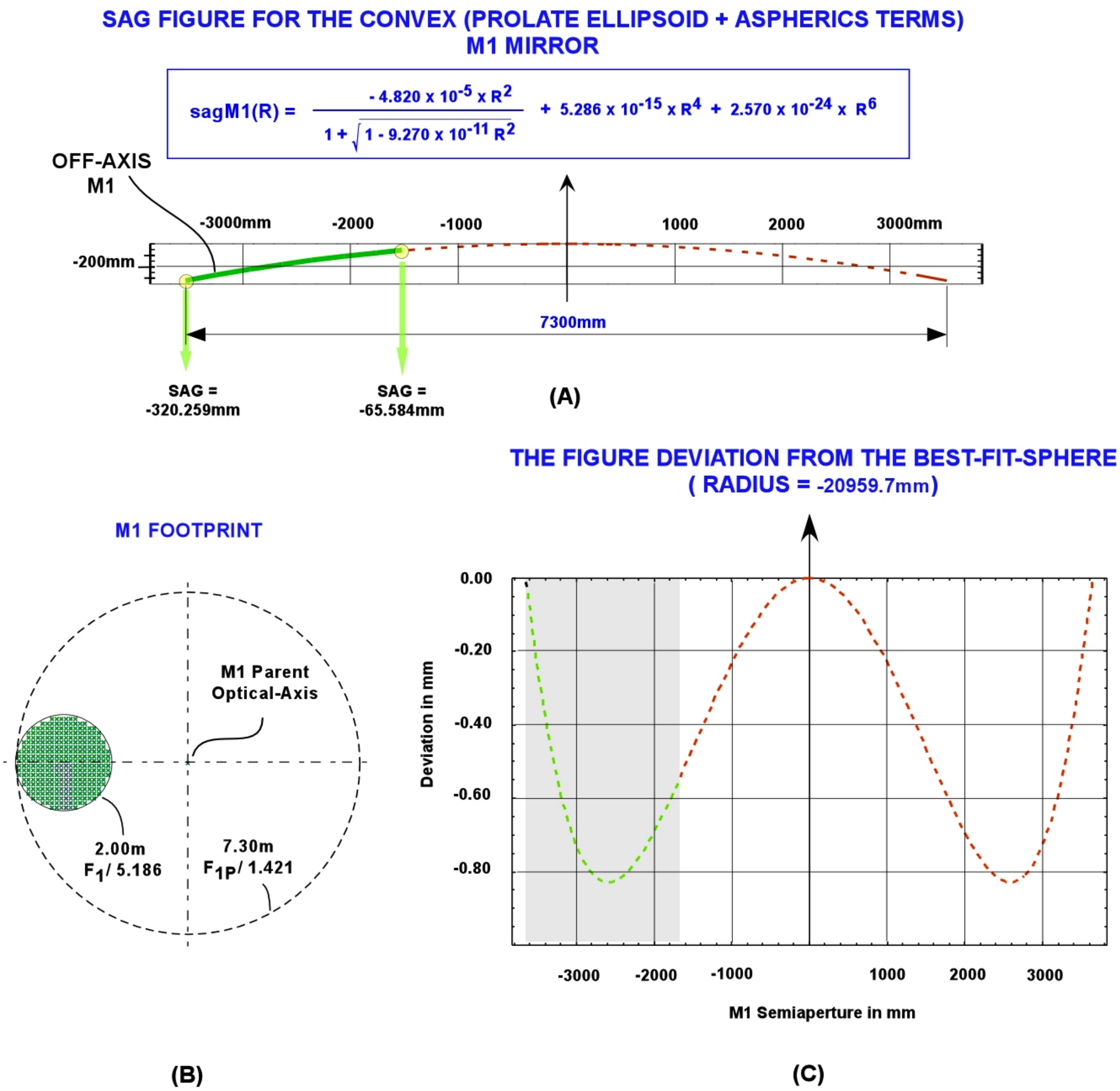

Figure 4 *– "Off-Axis" configuration for SNAP: (A) the sag equation for the primary mirror M1, an off-axis section of 2.0m F_1/5.186 of a F_{1P}/1.421 7.30m prolate spheroid (ellipsoid) parent primary mirror M1P, as showed on (B) its footprint. The figure deviation from the best-fit-sphere for the parent mirror M1P is showed in (C) where the shadow region represents the deviation for the off-axis section M1, the maximum deviation is –0.8283mm at R=2600m.*

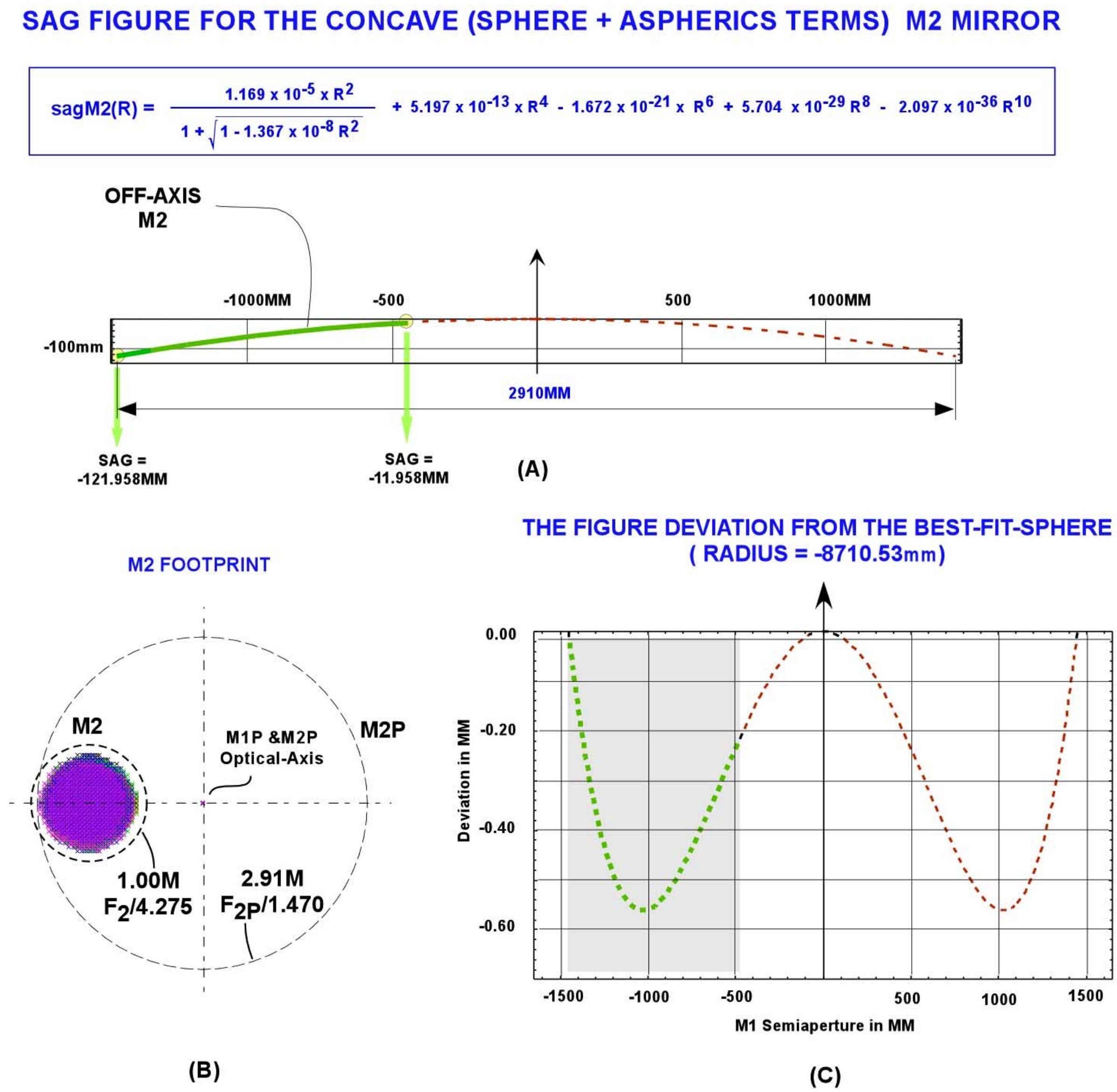

Figure 5 *– "Off-Axis" configuration for SNAP: (A) the sag equation for the secondary mirror M2, an off-axis section of 1.00m F_2/4.275 of a F_{2P}/1.470 2.91m aspherical parent primary mirror M2P, as showed on (B) its footprint . The figure deviation from the best-fit-sphere for the parent mirror M2P is showed in (C) where the shadow region represents the deviation for the off-axis section M2, the maximum deviation is –0.559mm at R=1050m*

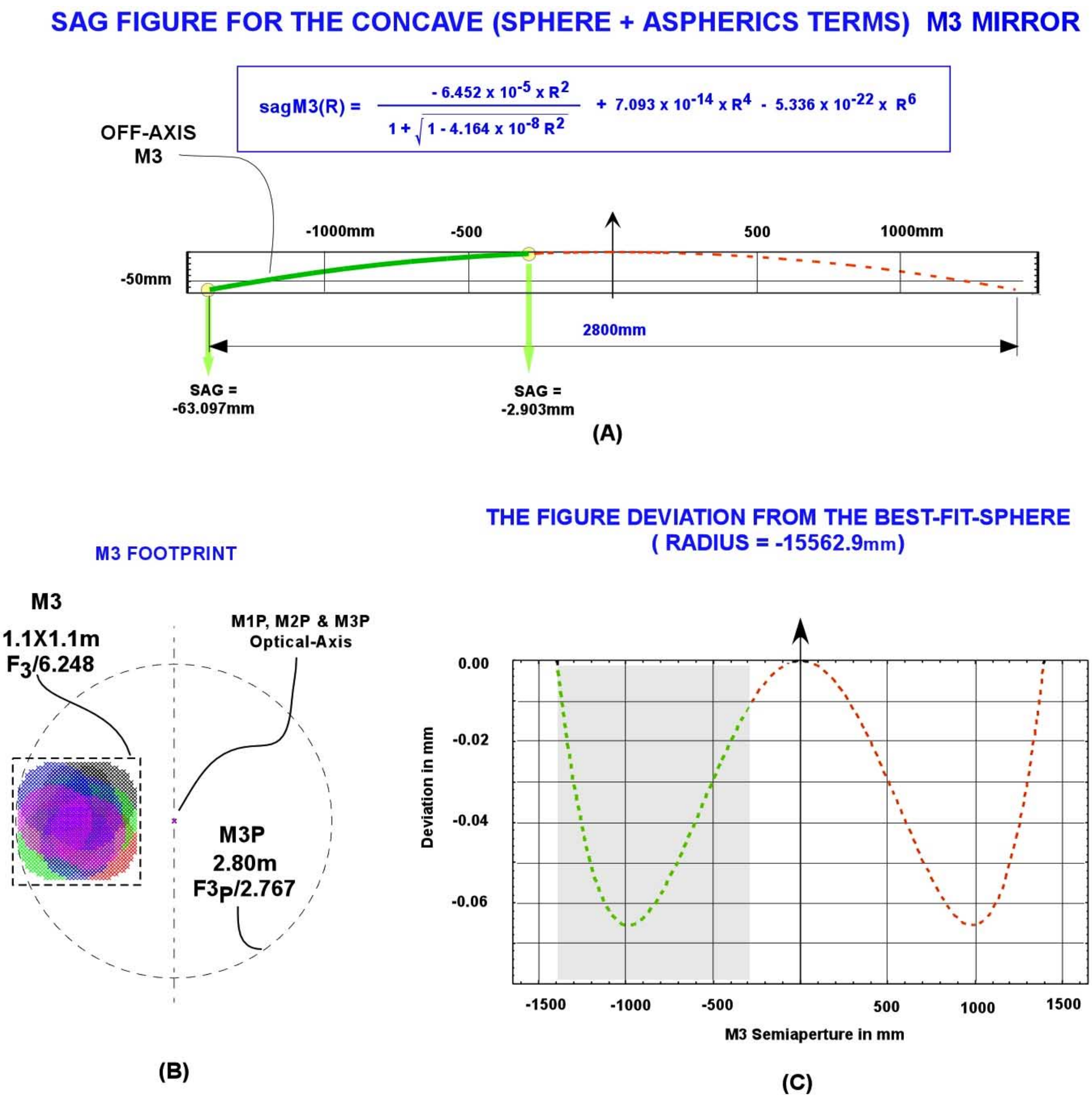

***Figure 6** – "Off-Axis" configuration for SNAP: (A) the sag equation for the tertiary mirror M3, an off-axis section of 1.1 x 1.1m F_3/6.248 of a F_{3P}/2.767 2.91m aspherical parent primary mirror M3P, as showed on (B) its footprint . The figure deviation from the best-fit-sphere for the parent mirror M3P is showed in (C) where the shadow region represents the deviation for the off-axis section M3, the maximum deviation is –0.0655mm at R=990m.*

2- SNAP "<u>ON-AXIS</u>" DESIGN

The *“On-Axis”* design for SNAP 2.0m $F_s/10$ system optimized across 1 Deg^2 FOV is also a three-mirror system with the tertiary mirror M3 placed far behind the primary mirror as proposed by Willstrop (1984). The system is a Paul system using a reflective Schmidt plate corrector of an afocal Cassegrain telescope, providing an anastigmat system and using a perforated primary, as proposed by Marsenne in 1636. This Willstrop-Marsenne-Schmidt system providing us with a possibility of place the focal plane (FP) outside the light beams from M2 and from M3, using a folder mirror M4 in the system exit-pupil position. The position and diameter of the system exit pupil is controlled during the optimizations to minimize the obscuration caused by M4. The system obtained is *almost* the same obtained by the SNAP preliminary study - September 2000. Figure 7 shows the SNAP *“On-Axis”* design layout - the primary M1 is a 2.0m $F_1/1.42$ a prolate spheroid (ellipsoid). The secondary M2 is a $F_2/1.37$ 0.44 m hyperboloid. The tertiary M3 is a $F_3/1.00$ 0.57x0.57 m square prolate spheroid mirror. The design prescription is presented in Table 2.

Table 2 *– The optical prescription for the SNAP “On-Axis” $F_s/10$ design optimized across 1x1 Deg FOV. The effective focal length is EFL=20000mm and system plate scale is 10.3132 arcsec/mm.*

Surface M_i	***Curvature Radius*** *[mm]*	***Conic Constant***	***Thickness from M_i to M_{i+1}*** *[mm]*	***Optical Clear Aperture & Mirror Speed***	***Deviation (D_i) from the best-fit-sphere & Sag (S_i)*** *[mm]*
M1 Primary	*-5476.9498*	*-0.9745*	*-2240.6678*	*2.00m $F_1/1.42$*	*D_1 = -0.1853* *S_1 = -91.311*
M2 Secondary	*-1249.3071*	*-2.024148*	*3800.0000*	*0.44m $F_2/1.37$*	*D_2 = -0.0739* *S_2 = -19.219*
M3 Tertiary	*-1610.9095*	*-0.54897*	*-991.4634*	*Square :: 0.57x0.57 m* *$F_3/1.00$*	*D_3 = -0.1128* *S_3 = -51.278*
M4 Fold-Mirror (Exit Pupil)	*FLAT @45^0*	----	*1008.5366*	*Ellipse 0.137x0.203m*	---
FP Focal Plane	*FLAT*	----	---	*349.067mm x 349.067 mm*	---

The 20000mm system effective focal length (EFL) assures a plate scale of S=10.3132 Arcsec/mm that gives a focal plane of 349.067 x 349.067 mm^2. The optical performance of the system optimized over the 1Deg^2 FOV is represented by the encircled energy (EED) distribution for several positions F_i (x,y) across the FOV as showed in figure 9 . The geometric spots for the several positions F_i(x,y) are presented in figure 8. As presented in Table 2 the three-mirrors deviate very mildly from a best-fit-sphere not presenting difficulties to manufacture or test them.

One of the main constraints during the optical optimizations was the size of the exit pupil to minimize the size of the fold mirror M4 in this way minimizing the obscuration of M4 on the beam from M2. Positioning mirror M4 tilted 45^0 about the system optical axis, M4 size obtained is an ellipse of 0.137 x 0.203 m, yielding in an obscuration by area of 20.1% on the square 0.33 x 0.33 m^2 light beam from M2. This obscuration can be reduced to 10.4% by area if M4 is tilted of 18^0 about the optical axis, as is showed in figure 10. If SNAP can survives with the 1X1 Deg focal plane at side of mirror M3, we can economize 10% of obscuration!

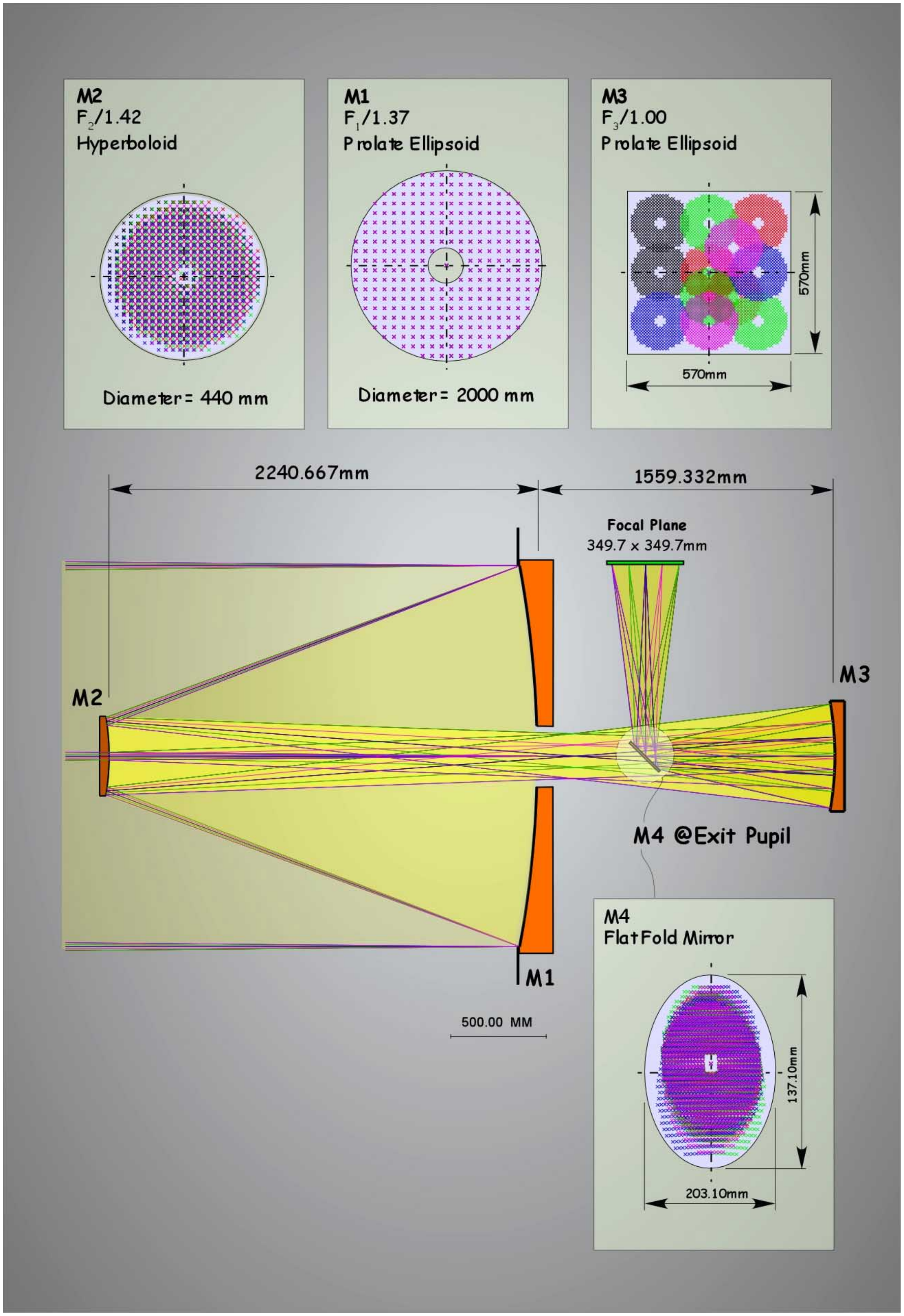

***Figure 7 – "On-Axis" configuration for SNAP**. A Willstrop-Marsenne-Schmidt system optimized over 1Deg^2 FOV producing a F_s/10 with 20000m of effective focal length. The footprint for each mirror is showed in detail.*

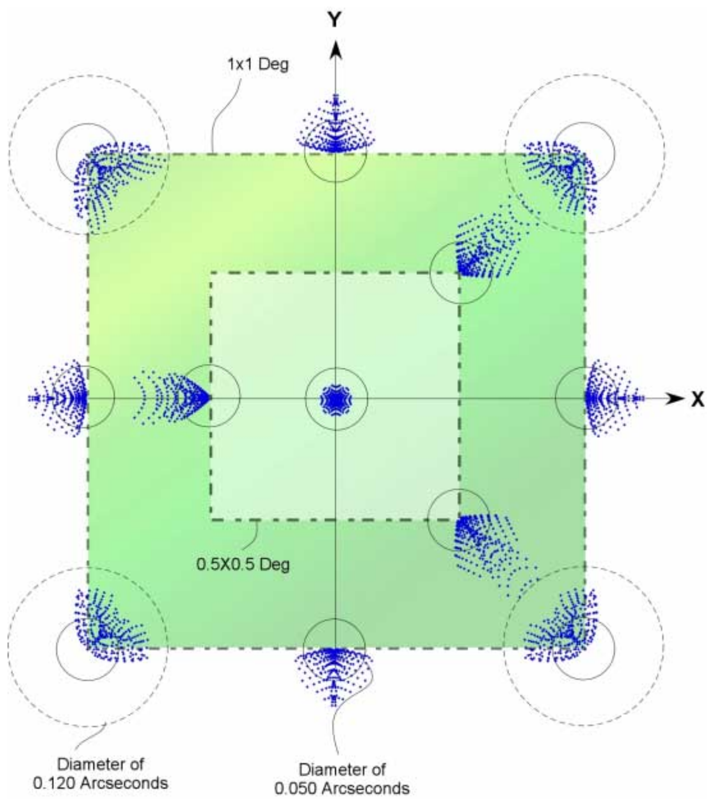

Figure 8 *– The "Off-Axis" SNAP design geometrical spots performance. Spot are computed over a 1X1 Deg FOV. Note that the frame dimension is not in the same scale than the spots diameters.*

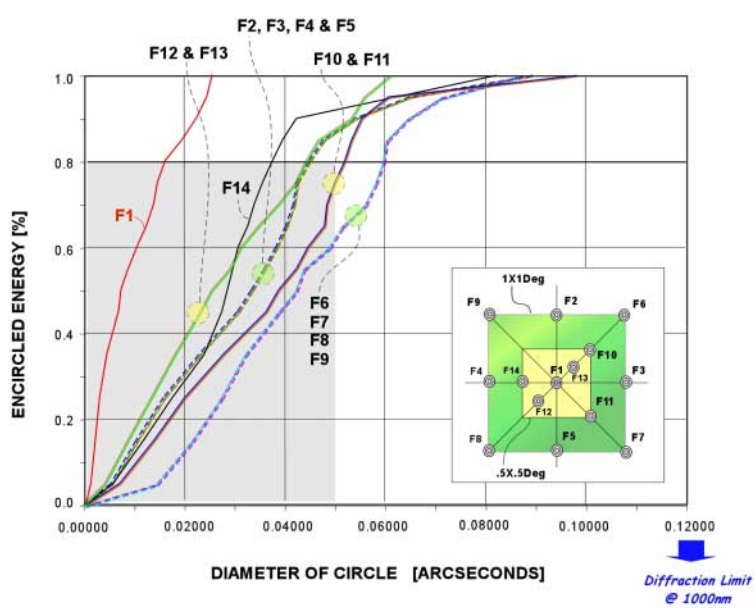

Figure 9 *– The "On-Axis" SNAP design encircled energy diameter for each field position $F_i(x,y)$ across the 1X1 Deg FOV as represented at right-side of the figure.*

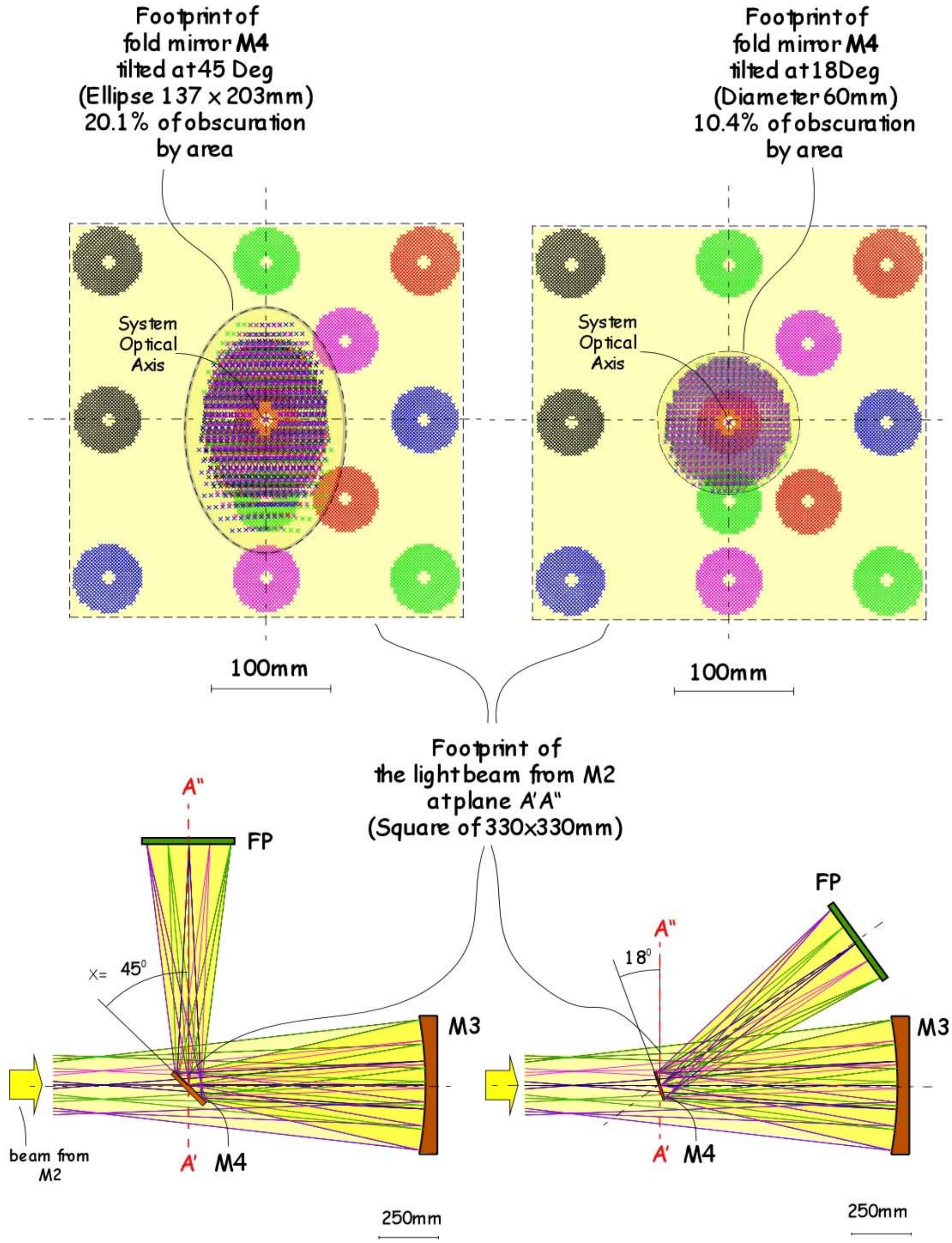

Figure 10 *- Positioning mirror M4 tilted 45^0 about the system optical axis, M4 size obtained is an ellipse of 0.137 x 0.203 m, yielding in an obscuration by area of 20.1% on the square 0.33 x 0.33 m^2 light beam from M2. This obscuration can be reduced to 10.4% by area if M4 is tilted of 18^0 about the optical axis.*

Using the same Willstrop-Marsenne-Schmidt design configuration – M3 placed far behind the primary mirror M1 – it is possible to generate another possibility for the "On-Axis" SNAP system. Tilting the tertiary mirror M3 of 9.5^0 about the system optical axis we can avoid the obscuration of the focal plane (FP) on the light beam from M2 to M3 and eliminate the use of a fold mirror M4. Figure 11 presents the optical layout of this system. The drawback is that the focal plane needs some curvature (R_i = 1609.968 mm). If SNAP can accept correct the FOV curvature with a kind of refractive "flatter" just before the focal plane integrated to the dewar window this design became also very attractive.

The optical performance of this possibility is almost the same than the others designs, the mean value of the blur circle diameter with 80% of encircled energy for 12 spot positions across the 1x1 Deg FOV is 0.103 Arcsec. The obscuration by area of the secondary mirror M2 on the primary M1 is 10.90%.

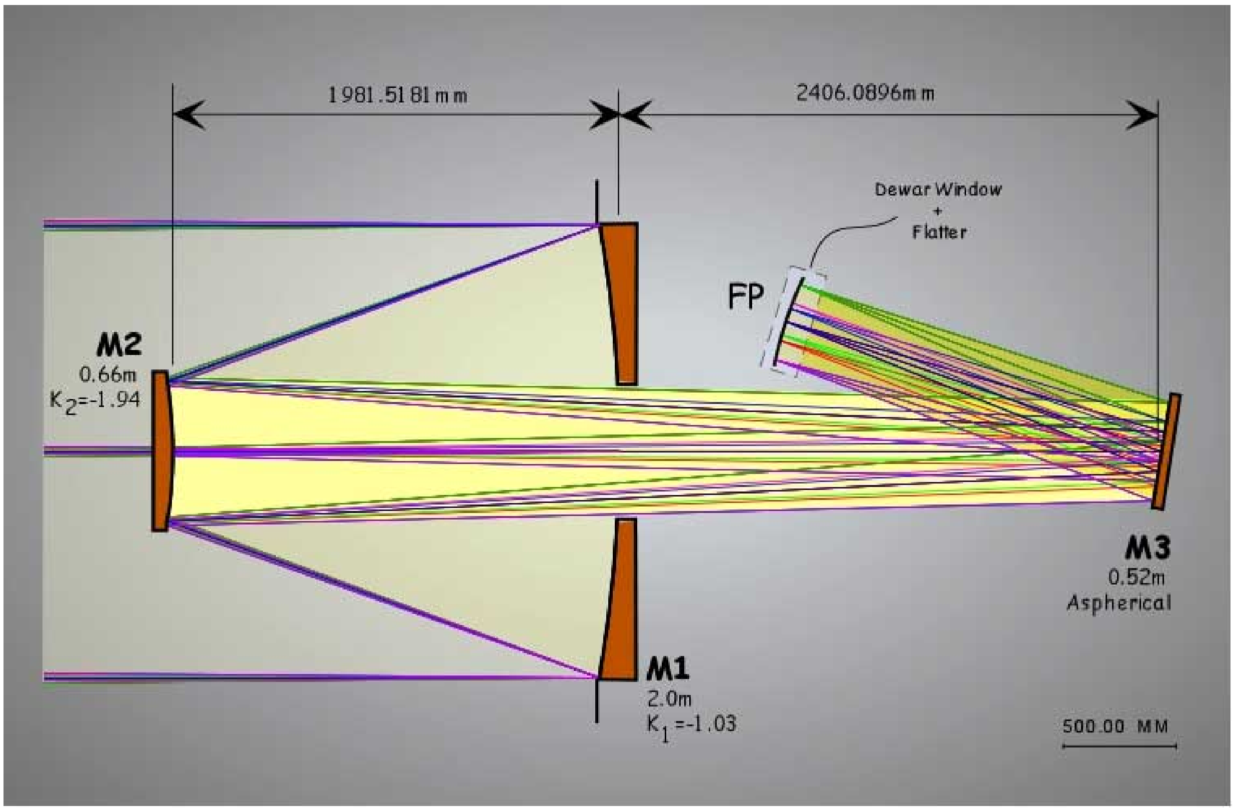

Figure 11 *– "On-Axis" SNAP, a tilted possibility! The tertiary mirror is a "quasi-flat" (R=-834364.539mm) mirror with surface conic coefficient $K_3=0$ plus the 4^{th} ($A = 5.829 \times 10^{-11}$) order deformation coefficient. One can envisage M3 as a reflective Schmidt as corrector of the afocal telescope M1+M2.*

3 – TWO DESIGNS

Two basic designs – *"On-Axis"* and *"Off-Axis"* – have been optimized for SNAP 2m $F_s/10$ across $1Deg^2$ FOV. The *"On-Axis"* design obtained here confirm the three-mirror anastigmatic design obtained before by SNAP team preliminary study, Sept. 2000 report on the web. It also confirm the drawback imposed by the *"On-Axis"* three-mirror design **an appreciable central obscuration by area of 20%**, even constraining the system optimization to a minimal exit pupil diameter. **A possibility to reduce the obscuration to a 10% value by area** is presented using the fold-mirror M4 tilted of 18^0 about the optical axis instead of the canonical 45^0 . The disadvantage is that this design imposes to place the 1X1 Deg focal plane at side of mirror M3.
A preliminary idea of using the same three-mirror system where the mirror M3 placed far behind the primary M1 but tilted of $9{,}5^0$ about the optical axis is also proposed. The deal of using this design is that we eliminate the fold-mirror M4 and only the secondary mirror M2 is responsible for the central obscuration of 10.9%. The drawback on this design is that the Petzval sum is not zero and the flat field is not achieved, although a flatter could be used just before the focal plane integrated to the dewar window.

All these *"On-Axis"* designs require, the mirror M3 placed far behind the primary M1 in order to provide an optimum image position (FP) and imposes the use of a tilted flat mirror M4 at the system exit pupil position to translate the focal plane at an orthogonal direction of the system optical axis, resulting in an 4-mirror and 2-axis system, increasing the complexity of the optical surfaces support structure – a complex baffling design - and consequently increasing the scattered light, and lower PSF efficiency because of obscurations and multiple diffuse reflections from the telescope support structure .

Rethinking all the drawbacks using an *"On-Axis"* we proposed here a new and exciting new concept *"Off-Axis"* design for SNAP. It offers the opportunity to develop an extremely efficient 2m F/10 telescope optimized over a $1Deg^2$ FOV, delivering a better optical performance than the "On-Axis" design with an **unobstructed aperture** and three reflections. Also there is no doubt that the off-axis design offers better efficiency and lower scattered light properties compared to the *"On-Axis"* design, that means a reduction on the time-dependent or field-dependent systematic scattered light background noise. This has important implications for telescopic observations of any faint source in the presence of a nearby or out-of-field bright source.

The *"Off-Axis"* design, as a new concept, has some concerns that have to be resolved and some already was partly resolved by earlier studies. One of the concerns is the techniques suited for **aligning the off-axis optics**. Some studies done before (NPT Proposal , IFA/UH -1999) has proposed the use of wavefront sensors to measure the aberrated beam and compared to the ray-trace-model stipulating corrective measures obtaining in this way a collimation state of the system. The **tolerances** to built an off-axis system has to be tighter, but the **sensitivities** of the system will be almost the same of an on-axis system, because each surface is only decentered not tilted about the optical axis of the system, this means that the system lose the circular symmetry of an on-axis system (figure 8) but preserve the bilateral symmetry (figure 2). Also as mentioned before, in the particular case of the "Off-Axis" SNAP design the vertexes of M1&M3 and M2&FP are coincident and collinear to the optical axis of the system, that was intentionally constrained during the optical optimization having in mind facilitating the alignment/tolerances and sensitivity tasks! The misalignment of an off-axis system are quite different for an off-axis system and require further study for better understand.

Another issue to an off-axis system is the **optical surfaces fabrication**. Several polishing companies (REOSC, Raytheon and Kodak) have manifested great interest in fabricate **large** off-axis surfaces up to 8m sections. Also note that the two-meters class off-axis optics has become *"a canonical routine"* after the construction of the two Keck telescope! In the case of SNAP, where the optical surfaces are not so large from 1.0 to 2.0m with mild aspheric departure, all the optical surfaces are manufacturable. One can manufacture the aspheric surfaces by using diamond grinding followed by computer-controlled polishing techniques. How about optical testing? It is well know that for an optical surface, *"it could be fabricated, if it could be tested"*. Again after Keck telescope, equipment for testing an off-axis segment from a parent mirror up to 11m already exists – the parents for SNAP M1, M2 and M3 are respectively 7.30, 2.80 and 2.91 meters!

For sure all these optical issues, alignment, tolerance, fabrication and testing, will require further studies before SNAP team take a decision on which design will be more convenient. I would be happy in participating of that.

Thanks for the opportunity,

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